Guest Editorial: Grid Forming Converters Placement and Utilisation to Enhance Transmission and Distribution Performances Under High Penetration of Inverter-Based Resources

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Abstract

Power systems around the world are rapidly transitioning to much higher shares of inverter-based resources (IBRs) with few synchronous generators remaining online. IBRs and synchronous generators have fundamentally different dynamic performance characteristics resulting in a difference in the overall power system dynamic performance. IBRs are generally more flexible and controllable than synchronous generators, however at the same time exhibit significantly more complex control systems. Furthermore, new and emerging capabilities are being developed progressively and in particular the so-called grid-forming inverters. Grid-forming inverters (GFM) offer several new capabilities not previously possible with conventional grid-following inverters (GFL). However, they are not well understood currently when applied in a mega scale and moving forward when they will likely take over the role synchronous generators have been performing for several decades as the workhorse of system security support. Key questions currently in the technical community include the extent to which GFM shall be similar or different to each of the synchronous machines and conventional GFL, and how various control strategies can assist in maximising the grid support capabilities sought and minimise or ideally eliminate any adverse impacts. The objective of this special issue is to provide insights into some of these unknowns.

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Introduction

Power systems around the world are rapidly transitioning to much higher shares of inverter-based resources (IBRs) with few synchronous generators remaining online. IBRs and synchronous generators have fundamentally different dynamic performance characteristics resulting in a difference in the overall power system dynamic performance. These differences will become more prevalent as IBR uptake increases in the power system. Reductions in system strength, inertia, damping of small-signal oscillations, fault levels, and other synchronous characteristics are the results of the transition from power systems with the dominance of synchronous generators to those with very few synchronous generators online.

IBRs are generally more flexible and controllable than synchronous generators, however at the same time exhibit significantly more complex control systems. Furthermore, new and emerging capabilities are being developed progressively and in particular the so-called grid-forming inverters. Grid-forming inverters (GFM) offer several new capabilities not previously possible with conventional grid-following inverters (GFL). However, they are not well understood currently when applied in a mega scale and moving forward when they will likely take over the role synchronous generators have been performing for several decades as the workhorse of system security support. It is also noted that similar to the GFL, GFM are current limited devices, and cannot be practically expected to address several grid needs at the same time as the solution for each problem will likely involve the provision of a portion of the total current available. Furthermore, like any other generation technologies including synchronous machines or conventional IBR, GFM have their own susceptibility and instability mechanisms. These limitations shall be accounted for along with their capabilities when designing the future power system and defining the technical requirements these inverters are sought to deliver.

Key questions currently in the technical community include the extent to which GFM shall be similar or different to each of the synchronous machines and conventional GFL, and how various control strategies, whether commercially available or under research and development, can assist in maximising the grid support capabilities sought and minimise or ideally eliminate any adverse impacts. The objective of this special issue is to provide insights into some of these unknowns.

Papers in the Special Issue:

11 papers were accepted for this special issue covering a wide range of subject matter expertise encompassing academia and research organisations, networks owners, system operators, original equipment manufacturers and consultancies. Of the proposed topics in the call for paper the following were addressed by the authors.

- Grid-forming inverter design philosophies including virtual synchronous machine/generator, droop, virtual oscillator control
- System strength support
- Black start provision in bulk transmission networks
- Angular stability, including both the small-signal and large-signal (transient stability) impact
- Unintended consequences
- Modelling and model validation

Below provides a description of each of the accepted papers.

An Overview of Stability Challenges for Power-Electronic-Dominated Power Systems: The Grid-Forming Approach (Shakerighadi et al.) focuses on power system stability aspects brought by the introduction of IBR and in particular the evolution from GFL to GFM control concepts. In doing so, the authors not only discuss the possible advantages of GFMs but also the concerns raised by several transmission system operators (TSOs). The paper includes a summary of Class 3 GFM control strategy and discusses the suitability of four main GFM control schemes to align with those requirements. Reduction of system inertia holds the first position in the ranking of stability challenges identified by various European TSOs followed by a few other technical challenges such as resonances due to cables and reduction of transient stability margins. Some of the developments to address these challenges are discussed. This is followed by several simulation results from different GFM control strategies where the use of the exact system frequency information is shown to play a crucial role in improving GFM performance.

Grid Forming Inverter and its Applications to Support System Strength – A Case Study (Zhou et al.) proposes hardware-in-the-loop testing of a GFM with a virtual synchronous generator (VSG) control with configurable inertia contribution. The objective is to investigate its capability to actively suppress sub-synchronous oscillations and to provide an inertial response. The effectiveness of GFM controls with battery energy storage systems (BESS) in improving system strength and transient stability have been demonstrated using electromagnetic transient (EMT) modelling of the transmission network in the Queensland, Australia. The study shows that with proper tuning and coordination with other generation in the area, the GFM BESS can address low system strength related stability issues including sub-synchronous oscillations, voltage stability and transient stability.

"Improving grid strength in a wide-area transmission system with grid forming inverters" (Mayer et al.) presents GFM as a viable option for system strength reinforcement using a wide-area EMT model of Aus-

tralia's National Electricity Market (NEM) power system. This model is already used for practical decision makings on power system operation, planning and generator connection. Vendor-specific GFM models are then integrated into the wide-area model and their performance is compared to that achieved from already connected synchronous condensers. Besides indicating promising results, the paper also highlights some limitations with respect to GFM current limitations and oscillatory control characteristics. Studies demonstrate the stabilising properties of centralised and decentralised or spatial application of the GFM as a credible technical alternative to synchronous condensers in mitigating sub-synchronous control interactions previously experienced due to the interaction of multiple GFLs under low system strength conditions.

An Adaptive Multi-Mode Switching Control Strategy to Improve the Stability of Virtual Synchronous Generator with Wide Power Grid Strengths Variation (Liu et al.) proposes an adaptive multi-mode switching control strategy for use in a VSG-type GFM. The shortcomings of the two existing types of implementations for VSGs are discussed. The authors point out that the power support approach has good dynamic performance in strong grids but poor performance in weak grids, and the voltage support type has good stability in weak grids but with oscillatory power output in strong grids. The shortcomings of the single control structure are therefore attributed to grid strength variations. An adaptive control with switching between the two operating modes is suggested to address this limitation. Identifying the grid impedance is the first important task. To avoid frequent switching between the two modes, a hysteretic boundary characteristic is added. The performance of the proposed adaptive switching algorithm is then assessed using simulation studies indicating a good response in power control mode for a strong grid and in voltage control mode for a weak grid.

An Application of Four-Wire Grid-Forming Power Inverter in Unbalanced Distribution Network (Döhler et al.) presents a detailed model for a GFM control based on two loops: an inner current control with a proportional integral (PI) controller and an outer voltage loop with a proportional (P) controller. The topology suggested is a three-phase four-leg four-wire topology, capable of operating in grid-connected or islanded mode if there is a need to provide the reference voltage and frequency for the AC bus. The model used includes three grid-connected photovoltaic (PV) systems connected via GFL inverters operating in parallel with the electric utility grid to emulate the dynamics of a power system with high share of distributed generation. Simulation studies indicate stable operation of the GFM with a sinusoidal voltage and frequency. Furthermore, the proposed GFM strategy exhibits effective voltage balance control where during the islanded mode of operation the unbalance factor (the ratio of negative to positive phase sequence voltage) is well below the 2% acceptable level.

Asking for Fast Terminal Voltage Control in Grid Following Plants Could Provide Benefits of Grid Forming Behavior (Ramasubramanian et al.) discusses that in IBR dominated power systems, it is possible to observe GFM inverter behaviour from a conventional IBR with a control structure based on a phase-locked-loop (PLL). This is demonstrated by analysing the stability behaviour of a conventional IBR by switching its control strategy from reactive power to voltage control. Analytical time domain results are further shown with small signal analysis including identification of participation factors. A key observation is the efficacy of fast voltage control to ensure system stability. The analysis also demonstrates similarities between various GFM control strategies with regard to fast voltage control characteristics.

Impedance Modeling and Stability Analysis of MMC with Different Types of Grid-Forming Control Schemes (Guo et al.) investigates the impedance-based stability characteristics of two GFM control schemes for modular multilevel converters (MMC): power synchronisation control (PSC) and direct power control (DPC). Using the harmonic state space, the equivalent impedance models of PSC-MMC and DPC-MMC are developed accounting for all controllers and MMC internal dynamic characteristics. Impedance shaping effects of main controllers are further analysed to identify the frequency bands where the MMCs have negative resistive impedance characteristics. Finally, potential instability phenomena in interconnected power systems are discussed using simulation case studies, and the virtual impedance method is introduced as a stabilisation control scheme. EMT simulation results demonstrate the accuracy of impedance models, and the positive impact of the stabilisation control scheme.

An improved damping adaptive grid-forming control for black start of PMSG wind turbines (Meng et al.) investigates an improved damping method for GFM control in permanent magnet synchronous generator (PMSG)-based wind turbines. The proposed control aims to suppress system frequency fluctuations and achieve a smooth black start from the wind turbine. The paper also presents detailed black start process in a microgrid with two PMSG-based wind turbines and energy storage. It is shown that, compared to the conventional GFM controls, the proposed control scheme can not only suppress frequency fluctuations better, but also achieve a smooth formation of the grid. Hardware-in-the-loop tests are also carried out to validate the proposed control strategy for achieving a smooth black start.

Damping torque coefficient analysis of PMSG-based WT with VSG control considering wind turbine dynamics (Qu et al.) uses the damping torque coefficient analysis (DTCA) for studying the small-signal stability of PMSG-based wind turbines under VSG control with consideration of wind turbine dynamics. Authors discuss that wind turbine dynamics can result in system instability, and propose that the minimum value of VSG damping control parameter shall be maintained to ensure system stability under all loading conditions below the rated wind speed. Simulation results from a single PMSG connected to a large grid with and without consideration of wind turbines dynamics are compared to verify the accuracy of the proposed analytical models and to evaluate the impact of control and system parameters on the system stability.

Assessment and Enhancement Control for Small-Signal Voltage Stability of VSC-HVDC Systems Supplying Passive Industrial Loads (Xue et al.) conducts small-signal voltage stability analysis for voltage source converter (VSC)-HVDC systems supplying industrial induction motor loads. The authors also propose stability enhancement control for the VSCs. Eigenvalue analysis is carried out to determine key factors influencing voltage stability. The analysis demonstrates that decreasing either the proportional gain of the VSC's PI controller or the electrical distance between the VSC and induction motor is detrimental to voltage stability. The proposed control strategy adopts virtual reactance and virtual admittance control for the VSC to improve the voltage control capability. The effectiveness and robustness of the proposed enhancement control is validated with time-domain simulations in a multiple induction motor system supplied by VSC-HVDC.

Hierarchical control scheme for proportional power sharing and robust operation in multiple virtual synchronization-based DC/DC converters (Ji et al.) proposes a hierarchical control scheme to achieve higher efficiency and superior anti-disturbance ability for multiple DC/DC converters with virtual synchronization-based control. In the primary control layer, the power sharing among different converters can be equalized with the additional regulation signals from neighbouring weak communications to eliminate the influence of line parameter mismatch among the converters. In the secondary control layer, the extended disturbance-observer-based backstepping control is proposed to eliminate external power fluctuations on the whole system. Two control levels are integrated as the hierarchical control architecture to realise different control objectives in different time scales. Theoretical analysis and simulations are presented to show the benefits of the proposed hierarchical control scheme.

Babak Badrzadeh holds BSc, MSc and PhD all in the area of electrical power systems. Prior to joining Aurecon in March 2021, he was with AEMO as the Manager of Operational Analysis and Engineering team. He is currently the Technical Director, Power Systems with Aurecon, and an Adjunct Professor with Monash University. His focus area is power system modelling and analysis, including the impact of grid-connected and distributed inverter-based resources from operational, connections and planning perspectives. He has played a key role in the worldwide establishment of wide-area electromagnetic transient (EMT) modelling, and the overarching area of system strength. Babak is currently the Convener of CIGRE Working Groups C2.26, having successfully convened working groups B4.83 and C4,56. In January 2021 Babak was appointed as a Distinguished Lecturer by IEEE Power and Energy Society (PES). He is also a recipient of 2019 ESIG Engineering excellence award. In March 2021 Babak was appointed as the chief editor of CIGRE Green Book on ‘’Power system dynamic modelling and analysis in evolving networks”.

Julia Matevosyan is a Chief Engineer at Energy Systems Integration Group (ESIG) and has more than 20 years of experience in the power industry. Prior to joining ESIG, Julia was the Lead Planning Engineer of the Electric Reliability Council of Texas (ERCOT). In her time with ERCOT, she worked on adequacy of system inertial response, system flexibility, frequency control and performance issues related to high penetration levels of inverter-based generation and ancillary services market design. Julia received her BSc from Riga Technical University in Latvia, and her MSc and PhD from the Royal Institute of Technology (KTH) in Sweden.

Zia Emin holds B.Sc., M.Sc., and Ph.D. degrees, all in electrical engineering. He is a specialist power system consultant with significant experience in power quality and switching studies initially with National Grid and later with Parsons Brinckerhoff (later WSP) and PSC. He has extensive knowledge in all aspects of power system modelling including steady-state, frequency- and time-domain modelling and substantial experience in harmonic performance specification for HVDC converter stations, renewable generation connections and the connection of traction supply points. He is Fellow of the IET, Senior Member of IEEE, Honorary and Distinguished Member of CIGRE and a Chartered Engineer in the UK. He is member of GEL/210/12 Committee at the BSI and of WG8 in IEC SC77A. He was the Chairman of CIGRE SC C4 System Technical Performance from 2016 to 2022. He received the CIGRE Technical Committee Award in 2013, the Distinguished Member award in 2014, the Honorary Member award in 2022 and the Senior and Principal Professional Associate titles within Parsons Brinckerhoff reflecting recognition on his technical and professional level. He has served in several colloquia, symposia and conference technical committees and continues to do so. He has over 60 technical publications and is a reviewer in many technical journals of IET, IEEE and other publishers.

Chao Lu received the B.S. and Ph.D. degrees from Tsinghua University, Beijing, China, in 1999 and 2005, respectively. He is currently a professor and deputy dean with the Department of Electrical Engineering, Tsinghua University, and is also a Changjiang distinguished professor of the Ministry of Education of China. His research interests include power system stability analysis and control, traction power supply technology for rail transit. He is the PI of multiple scientific research projects including the National Natural Science Foundation of China and the National Key R&D Plan, and has won several scientific and technological awards such as the second prize of the National Technological Invention Award, the first prize of the Ministry of Education's Technological Invention Award, and the first prize of China's Power Science and Technology Award. He has also won China Youth Science and Technology Award, Mao Yisheng Beijing Youth Science and Technology Award, etc.